

# Observations on the Luminosity Lifetimes, Emittance Growth Rates and Intra-Beam Scattering at the Tevatron

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## Abstract

A record luminosity of  $4 \cdot 10^{31}$  has been reached at the Fermilab  $p - \bar{p}$  collider. The lifetime of this luminosity at the beginning of the store is about 9 to 10 hours. This lifetime can be explained by the measured loss of antiprotons and protons due to collisions and emittance growths. We report on transverse emittance growth rates based on our Synchrotron Light Monitor. Longitudinal emittance growth rate measurements are based on the TeV Sampled Bunch Display data. It is shown that Intra Beam Scattering is a significant source of emittance growth. We comment on other possible factors for these observed emittance growth rates. Finally, we comment on future luminosity lifetimes, as we hope to further increase our peak luminosity.

## INTRODUCTION & INSTRUMENTATION

The luminosity lifetime is a critical factor in reaching high integrated luminosity at any collider[1]. In this paper, we summarize the results based on various Tevatron instruments on the various factors determining the luminosity lifetime for the  $p/\bar{p}$  Tevatron collider.

The luminosity is measured by the CDF Cerenkov Luminosity Counter(CLC)[2]. The bunch intensities are measured by the Fast Bunch Integrator (FBI) connected to a wall current monitor [3] Although this is not the optimum way to determine the bunch intensity due to uncertainties in the measured offsets coming from the non-uniform beam structure, the precision of this device is adequate to establish the correlations shown below. The Sampled Bunch Display (SBD) [4] is used to measure the longitudinal profile of every bunch in the Tevatron ring. This device samples at 2 GHz, performs Gaussian fits and reports a measurement of the bunch length for the  $2 \times 36$  bunches every 3 seconds or so. The transverse emittances are measured at the beginning of the High Energy Physics phase (e.g., when the beam collides) with the Flying Wire[5] These wires create background at the experiments, so we do not fly them during the stores. Instead, we use the Synchrotron Light Monitor (SyncLite)[6], which measures the transverse beam profile in each planes without perturbing the beams. This device reports each bunch transverse size every 15 seconds. The emittances reported by FW and SL are reproducible with a typical rms of a few percent. However, the systematic error or absolute scale uncertainty, is much large, of the order of 20 to 30%, as indicated by the effective emittance measurement coming from the luminosity

counters<sup>1</sup>.

The data is collected via the Sequenced Data Acquisition system [7] The stores we consider here are from August 2002 through March 2003.

## LUMINOSITY LIFETIME

The Luminosity  $\mathcal{L}$  recorded by the collider detectors (CDF and D0) can be compared to the computed ones based on bunch intensities and emittances[8]. The normalized collision rate change vs time for a given pair of bunches (or the inverse of the luminosity lifetime) can be expressed as the following sum:

$$1/\mathcal{L} d\mathcal{L}/dt = 1/\lambda_a + 1/\lambda_p + 2/\sigma_a(d\sigma_a/dt)/(1 + \epsilon_p/\epsilon_a) + 2/\sigma_p(d\sigma_p/dt)/(1 + \epsilon_a/\epsilon_p) + 1/F dF/dt$$

where  $\lambda_a, \lambda_p$  are the antiproton and proton bunch intensity lifetimes, respectively.  $\sigma_a$  and  $\sigma_p$  are the beam widths, averaged over both transverse planes<sup>2</sup> and  $\epsilon_a$  and  $\epsilon_p$  are the transverse emittances. F is the hourglass factor, derived from the SBD bunch length measurements.

Each of these terms can be determined from data. The proton lifetime can be much shorter than the inverse collision rate due to poor machine tuning (slightly misplaced collimators or orbits, betatron tunes or chromaticities). For other “good stores”, the proton lifetime is the smallest component in determining this luminosity lifetime: the  $\bar{p}$  lifetime is typically 16 hours against  $\approx > 100$  hours for the proton beam. The emittance terms contribute to  $\approx 25$  hours ( $\bar{p}$  and  $p$ ) in all three planes. The self consistency of this simple derivation has been checked by comparing the measured luminosity lifetime to the sum of these other quantities, as shown on figure 1. Although reasonably good agreement is obtained (5 to 15%, relative, on the luminosity lifetime), the effective emittance growth is significantly larger than the measured (SL) emittance growth rates.

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## OBSERVATIONS OF EMITTANCE GROWTH AND INTRA BEAM SCATTERING (IBS)

We now concentrate on the proton emittance growth rates. This growth rate  $r_\epsilon = 1/\epsilon d\epsilon/dt = 2r_\sigma = 2/\sigma d\sigma/dt$  is typically a few percent per hour, in all three

<sup>1</sup>We define the effective emittance as  $\epsilon_{eff} = F N_a N_p / (4\pi \beta^* \mathcal{L})$

<sup>2</sup>We assume here that the horizontal and vertical emittance are not too different from each other, which is the case.

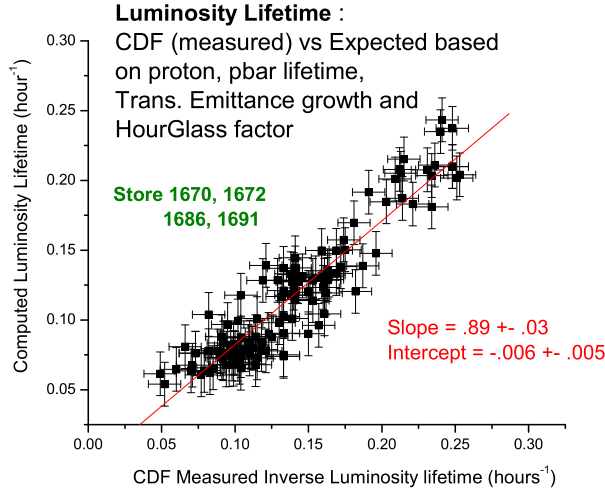


Figure 1: Correlation plot between the predicted (based on various emittance and intensity detectors) vs measured luminosity lifetime. One data point corresponds to one  $p\bar{p}$  bunch in a given store. This data was taken during August 2002. Similar results have been obtained on recent stores.

planes, at the beginning of the store.  $r_\epsilon$  itself decays with an approximate half-life of 5 hours. The grow rates reported from now on have been measured for the first 2.5 hours of the stores. The correlation between the horizontal and longitudinal growth rates shown on figure 2 is statistically significant, although there is a lot of fluctuations bunch to bunch and store to store. A similar correlation between the vertical and horizontal growth rates has also been observed.

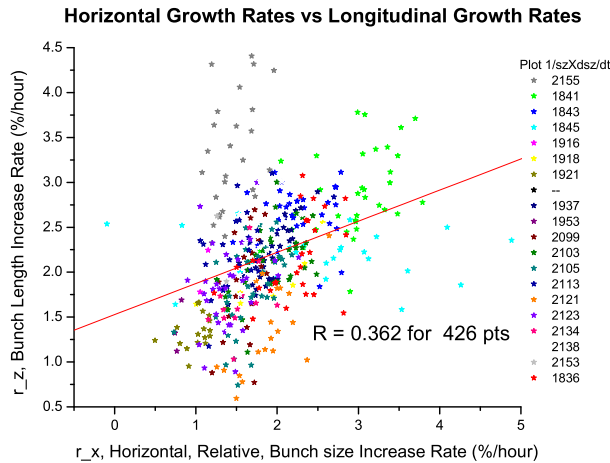


Figure 2: Correlation plot between the longitudinal and horizontal relative bunch size growth rates. Out of 15 store, only two of them showed no correlation. For all others, the probability that no such correlation existed is only a few percent, for each store.

We now show that these observed  $r_{\epsilon(x,y,z)}$  growth rates are qualitatively and semi-quantatively consistent with IBS. Following this theory[1], we compute these quantities taking into account the proper averaging of the dispersion and betatron function, including the straight sections. For elliptical beams, the emittance growth rate in the horizontal plane is (in the ultra-relativistic regime):

$$\begin{bmatrix} r_{\epsilon,x} \epsilon_x \\ r_{\epsilon,y} \epsilon_y \end{bmatrix} \approx \frac{L_c N_0 r_0^2 A x_{av}}{4 \sqrt{2} \gamma^3 \sigma_\tau \sigma_x \sigma_y \sqrt{\theta_x^2 + \theta_y^2}} \begin{bmatrix} 1 - \kappa \\ \kappa \end{bmatrix}$$

where  $L_c$  is the coulomb logarithm, taken in this calculation to be 28.108.  $N_0$  is the number of protons per bunch at low beta,  $\approx 1.7 \cdot 10^{11}$ .  $\gamma$  is the Lorentz relativistic factor, 1045.  $r_0$  is the classical radius of the proton,  $1.53 \cdot 10^{-15}$  mm.  $\sigma_\tau$ , the rms bunch length, expressed in sec ( $\approx 2$  ns).  $\sigma_x$  is the effective horizontal beam size (Gaussian  $\sigma$ ), averaged over the entire ring, respectively, taken to be:

$$\sigma_x = \sqrt{(\epsilon_{g,x} \beta_{x,av}) + (D_{av}^2 \sigma_p^2)}$$

$\epsilon_{g,x}$  is the rms geometrical emittance. Thus,  $\sigma_x$  includes the contribution due to dispersion. The lattice beta  $\beta_{x,av}$  and dispersion  $D_{av}^2$  functions are averaged over the entire lattice.  $\sigma_y$  is the vertical beam size, averaged over the entire ring.  $\theta_x, \theta_y$  is the angular spread of the beam (one  $\sigma$ ), excluding the contribution from dispersion, once again, averaged over the entire ring, in the horizontal and vertical planes, respectively.  $\kappa$  is the IBS transverse coupling factor.  $A x_{av}$  is length-wise average of the following combined Twiss function,

$$\frac{D_x^2 + (D_x \beta_x + \alpha_x D_x)^2}{\beta_x}$$

Likewise, longitudinally, we have,

$$r_{\epsilon,z} = \frac{d\epsilon_s}{\epsilon_s dt} = \frac{L_c N_0 r_0^2 \Gamma_s^2}{4 \sqrt{2} \gamma^3 \sigma_\tau \sigma_x \sigma_y \sqrt{\theta_x^2 + \theta_y^2}}$$

where  $\Gamma_s$  is  $(\sigma_\tau c)/\sigma_p$

The comparison data/IBS model is shown on figure 3. Once again, the correlation between predicted and measured values is statistically significant, once we reject the store or bunches for which the proton loss rate is anomalously high compared to the expected loss due to collisions at B0 and D0. The cause for such occasional short proton lifetime is not known for certain (slightly incorrect tunes, non-linear resonance whose effects are possibly amplified by beam-beam). In absence of betatron coupling, IBS predicts no growth rate in the vertical plane. Since we are running with significant coupling ( $\kappa \approx 0.3$ ), emittance growth is indeed observed in both transverse plane. Despite the reduction of the growth rate in the horizontal plane due to this coupling effect, the IBS prediction for most of the stores are significantly above the measured values, in the horizontal and longitudinal plane. We suspect that residual beam

losses could account for that discrepancy. Note also that we still have an unresolved discrepancy between the effective emittance growth rate (see above) and the measured (SL) emittance growth rates.

Other possible source of emittance growth have been considered.

- The longitudinal dampers stabilize the bunches during the stores. They do not affect such slow diffusion processes.
- We measure the low-level phase noise in the r.f. system and wrote a simple numerical simulation model of the longitudinal dynamics with such noise. The emittance growth rate was found to be small ( $\approx 25\%$ ) compared to IBS predictions.
- Poor vacuum in the Tevatron: The uncollided (small longitudinal emittance bunches) proton beam has a lifetime of about 500 hours. From this, and direct pressure measurements, we concluded that the beam heating from multiple scattering on residual gas was found to be small compared to IBS predictions.
- Other possible effect such as non-linear resonances or beam-beam effects have also been considered. However, we do not have firm quantitative results, due to the inherent complexity of such simulation.

## CONCLUSION

The Luminosity lifetime at the beginning of good (i.e., small unknown beam losses) store is about 9 to 10 hours, and increases to 15 to 20 hours at the end of the store. This lifetime is quantitatively ( $\approx 15\%$ , relative) understood in terms of beam losses and emittance growth. We compared these emittance growth rates with the IBS prediction and found semi-quantitative agreement. ( $\approx 50\%$ ) This work allows us to have some confidence in the model describing various luminosity upgrade scenarios[1]. We are planning to operate the collider at a peak luminosity of  $3.3 \cdot 10^{32}$  by raising both proton and antiproton beam intensities, while preserving the current emittances at injection. Under these circumstances, IBS is significant for both beams. The luminosity lifetime will then be  $\approx 5.4$  hours.

## REFERENCES

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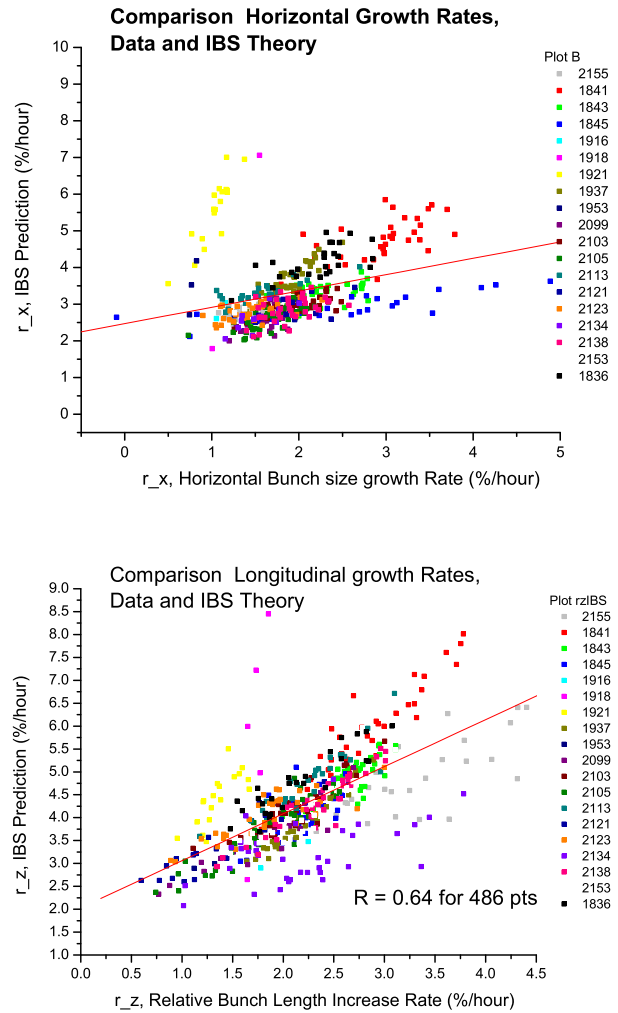


Figure 3: Correlation plot between the measured and IBS-predicted horizontal (top) and longitudinal (bottom) relative bunch size growth rates.

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